Chapter 10

SUMMARY AND RECOMMENDATIONS

The studies reported here were centered on two methods of estimating evaporation from bare soil - a direct method using microlysimeters (ML's) weighed daily, and an indirect energy balance approach which involved measurements of soil surface temperature, air temperature and wind speed. The performance of these methods was evaluated and improved.

Additional studies reported included those on irrigation uniformity and the time invariance and spatial variability of irrigation related parameters including depth of water in catch cans, profile water content after irrigation, and the change in storage due to irrigation.

The time invariance and spatial variability of evaporation (as measured by ML's) and soil surface temperature were also studied in an attempt to determine if microlysimeter and surface temperature measurements could be used together to reduce the number of ML measurements needed by replacing them with temperature measurements.

This chapter will summarize the results of these studies and recommend future actions. For more detail the reader is referred to the summaries and discussions at the ends of several chapters.

Microlysimeters

Two types of wall material (steel and plastic) and three lengths (10, 20 and 30 cm) were used in the ML study. Steel ML's were found to underestimate evaporation compared to plastic at the 20 and 30 cm lengths with the 14% reduction in evaporation at the 20 cm length being significant at the 10% level. The lack of significance for the evaporation difference at 30 cm length was attributed to the loss of some replicates and the imprecision with which microlysimeters were weighed in Experiment 1. A plot of cumulative evaporation vs. ML length showed signs of attaining a maximum for 30 cm plastic ML's but it could not be concluded that 30 cm ML's were long enough to prevent inhibition of evaporation at some point during the 9 days under the conditions of this study.

A sub-study of heat flux in ML's was conducted using 30 cm steel and plastic ML's and with one half the ML's open at the bottom and connected with the underlying soil and with the other half capped on the bottom with 6 mm thick PVC plastic disks. Steel ML's conducted heat to the subsurface much more quickly than did plastic with significant differences (1% level) in both phase (up to 3 hours earlier) and amplitude (up to 1 °C larger) of the diurnal temperature wave at 15 and 30 cm depths. Also, the amplitude of surface temperature in steel ML's was reduced by 2.7 °C compared to that for plastic

ML's (significant at 1% level). ML's with plastic bottoms exhibited subsurface temperature maximums up to 1 °C warmer than those open to underlying soil. The warmer temperatures are attributed to the insulative effect of the plastic disks.

Diurnal net soil heat flux was positive downward for all days but steel ML's averaged net heat fluxes 44% higher that those in plastic ML's. This heat was lost to the evaporation process and was undoubtedly the reason for the lower evaporation measured by steel ML's. Net diurnal heat flux in plastic ML's was quite similar to that in nearby field soil and averaged 0.7 mm (equivalent water evporated) compared to 1 mm for steel ML's. Darker soil surfaces in steel ML's on several mornings after irrigation lead to the hypothesis (unconfirmed) that higher subsurface temperatures in steel ML's were causing significant nighttime vapor transport of water from the subsurface to the surface.

Microlysimeters were found to be difficult and time consuming to install but easy to use after the first day. The study soil was so plastic when wet that ML's were installed before irrigation when the soil was solid enough to prevent much compaction. Initial extraction of 57 ML's required 16 person hours even with tools designed especially for the purpose. A portable electronic balance with ± 1 g precision and 5000 g capacity and a custom built portable wind screen were necessary to keep weighing time and precision within acceptable limits (about 50 minutes to weigh all 57).

Recommendations. Microlysimeters should be built of non-heat conductive material. The PVC plastic used in this study served well and had a thermal conductivity close to that of dry soil. Conversely the bottoms of ML's should be sealed with material that conducts heat at least as well as the surrounding soil. The plastic disks used in this study, and the rubber stoppers used elsewhere, disrupt the flow of heat to the subsurface and result in ML's which are hotter at all depths than the surrounding soil. Though the effect on evaporation of this disruption was not measured it would be foolish to invite it. In Experiment 3, I successfully used a thin non-stretching plastic tape known as "package sealing tape" to seal the ML bottoms.

Microlysimeters should be at least 30 cm in length to provide adequate storage of soil moisture if they are to be used to study evaporation over several days. In addition to the primary ML's, which are extracted immediately after irrigation, other ML's should be installed (at the same time as the primary ML's) but extracted on subsequent days. These ML's would serve as a check on both the degree of drainage from the upper profile and on the accuracy of evaporation measurements from ML's that were extracted soon after irrigation.

More sophisticated modeling of heat fluxes in microlysimeters should be attempted. A model based on the surface energy balance and including water as well as heat transfer would allow the results presented here to be extended to other regions with their unique weather conditions. Such a model could also serve to elucidate heat fluxes and their importance in larger weighing lysimeters.

Energy Balance Models

The energy balance model (EBM) of evaporation proposed by Ben-Asher et al. (1983) was used as a starting point for model testing and development. This model states that the latent heat flux from a drying soil must equal the difference, between a reference dry soil and the drying soil, of net radiation and of soil and sensible heat fluxes. Original model inputs were the difference between maximum diurnal soil surface temperatures for the dry and drying soils, ($T_{o,max}$ - $T_{d,max}$), and average daily wind speed. The original model was shown to be a worse predictor of evaporation than was the quantity ($T_{o,max}$ - $T_{d,max}$) alone.

Three major improvements were made in the EBM resulting in a more physically based and more accurate model. First, integrating with a half hour time step, instead of a 12 hour time step, allowed better interaction between temperature and wind speed effects. Second, the introduction of a relatively easy method of accurately estimating soil surface temperature at small time intervals at many points in the field resulted in much better predictions of evaporation. This method used infrared thermometer measurements of soil surface maximum and minimum temperatures at all locations in the field (2 measurements per day at all locations) in conjunction with surface temperature measured at 1 or 2 locations at small time intervals and recorded on a dedicated data logger.

The third improvement involved finding more appropriate forms of the transfer coefficients for the sensible heat fluxes from reference dry and drying soils. A transfer coefficient function for bare soil due to Kreith and Sellers (1975) was used for sensible heat flux from the drying field soil and this improved model performance. Likewise a "best fit" function for the transfer coefficient, $D_{H,o}$, for sensible heat flux from the reference dry soil improved the model. The empirical function indicated that sensible heat flux from the small and relatively hot disk, represented by the reference soil surface, was independent of wind speed and thus probably due to free rather than forced convection. These improvements resulted in an increase of 18 percentage points (0.55 to 0.73) in the r^2 value for regression of measured vs. estimated evaporation using Experiment 1 data.

Validation of the model with the Experiment 3 data set resulted in an r^2 value of 0.78 for the regression of measured vs. estimated evaporation. This larger and more precise data set was used to again find a best fit function for $D_{H,o}$ which was verified to be independent of wind speed and to have a constant value of 0.00383 m/s. The final EBM (EBM4) was relatively insensitive to the provenance of the soil temperature data measured at small time increments, performing equally well whether the measurements were made in a relatively wet or dry area of the field.

All versions of the EBM omitted the soil heat flux terms and the shortwave radiation component of the net radiation terms in the energy balance formulation. The omitted terms were evaluated to be 31% and 25% of average measured evaporation on the first day after irrigation for Experiments 2 and 3, respectively. On later days the omitted terms were as much as 300% of average evaporation. An attempt to correct model predictions, by adding a single daily value (equal to the omitted terms) to all EBM estimates, failed. Possible reasons for the failure were that albedos were estimated after the fact, and that heat flux in the dry soil could not be calculated directly because subsurface temperatures were not measured in the reference. Still it was clear that if the value of the omitted terms could be found for individual locations then the EBM would be improved.

Inaccuracy of the EBM may also have been tied to the transient nature of soil surface temperature. Soil surface temperatures at selected locations changed as much as 10 °C over the 30 to 40 minutes required to measure midday temperature at the 57 locations. The largest fluctuations in surface temperature were caused by passing clouds but abrupt changes in wind speed also appeared to affect temperature.

Recommendations.

Further model improvements will depend on finding methods of estimating the omitted soil heat flux and shortwave radiation terms. Field estimates of albedo may be made by eye, especially if the limits of albedo are known for the soil, and could be accurate enough for first order estimates of the radiation term. But the development of a portable hand held device, similar to the infrared thermometer in concept, would be very helpful. If such a device could be incorporated into the infrared thermometer both temperature and albedo could be measured simultaneously.

The drying soil heat flux term could be measured at one location and data recorded on the same device used to record weather data. If heat flux were relatively invariable in space this approach would appreciably improve the estimates of evaporation from the energy balance model. Measurement of soil heat flux in the reference is also needed.

Experimental work should be done to accurately measure the sensible heat flux from the reference dry soil. This problem seems daunting given the need to avoid interference with insolation and air movement over the reference but perhaps eddy correlation techniques are a valid path.

Since soil surface temperatures are especially labile at midday, some thought should be given to ways to correct point measurements so that they are more truly representative of the maximum diurnal temperature at each point. Surface temperatures could be recorded continuously at two locations (say a relatively wet and a relatively dry area) on a small time interval (say one half minute) during the time that surface temperatures at field locations were being taken with the infrared thermometer. Since temperatures at field locations were recorded on a Polycorder with timing capability it would be easy to synchronize readings and perform a correction on the temperatures at each field location.

Performance of EBM4 should improve under conditions of high evaporative demand during which the dry and drying soil albedos would quickly become similar. Performance should also improve if soil heat flux is small and is constant from day to day. Conditions such as these would most likely be found in summer in Arizona, a time when closed crop canopies are more prevalent than is bare field soil.

Time Invariance and Spatial Variability

Time invariance occurs when the ranking of sample locations by sample values is stable over time. If a variable is shown to be time invariant it may be possible to reduce the number of samples needed because locations representative of the mean and of extreme values of a variable may be identified. If both ranking and dispersion are stable over time then the relative variogram will also be stable, a fact that has positive implications for the use of a single relative variogram to represent spatial variability of a variable for different days.

Time Invariance.

Five variables measured at 57 field locations were examined to see if they were time invariant. Two of these, evaporation and soil surface midday temperature, were related to evaporation while two were irrigation related parameters - catch can depths and the change in storage due to irrigation. The fifth variable, profile water content was examined both as it related directly to irrigation (profile water content on the day after irrigation) and in the context of longer term evaporation and drainage using data from succesive days after irrigation.

Three measures of time invariance were used. The first two, simple correlation of data between days and Pearson rank-order correlations, gave similar results. Both methods gave correlation coefficients near one if the ranking of the data remained relatively constant. The third criterion was stricter and involved correlations between days of the relative difference values. The relative difference was defined as the sample value minus the mean with the difference then divided by the mean (Equation 8-4). Correlation values near 1 were again indicative of time invariance but regression slopes near one and intercepts near zero could also be expected if the standard deviation (dispersion) remained constant with time.

The only variable shown to be unequivocally time invariant was the profile water content. The profile water content data presented here were more clearly time invariant than those presented by Kachanoski and De Jong (1988) and Ottoni (1984). Contrary to the report of Kachanoski and De Jong (1988), the linear correlation of relative differences for profile water contents had a slope that was close to 1, often significantly so, showing that these data were time invariant according to the criterion of Equation 8-4 proposed by those authors. Data for profile water contents of a silty clay, presented by Vachaud et al. (1985), appear to be similar to those presented here.

The lack of correlation for the change in storage due to irrigation is a similar result to the lack of correlation for recharge reported by Kachanoski and De Jong (1988). Catch can data time invariant according to the ranking criteria but not according to the stricter criterion of Equation 8-4.

Since profile water contents were very well correlated across irrigations for Experiment 2, while midday surface temperatures were not, then profile wetness is probably not a good indicator of surface temperature nor of evaporation which is well correlated with midday surface temperature. This does not mean that surface water content is not well correlated with either temperature or evaporation since no data were presented on surface water content.

For Experiment 3, evaporation was well correlated (both Spearman and linear correlations) for days after a given irrigation, there was enough dispersion in the data to render problematic the picking of a site representative of the mean. The same was true for the surface temperature data. Neither variable was time invariant by the stricter criterion of Equation 8-4. Thus the time invariance of surface temperature and evaporation were not clearly established. Each sample location was moved 1.5 m west after the first irrigation of Experiment 3. The lack of rank correlation across irrigations, for the temperature and evaporation data, indicates that the range of autocorrelation for these variables was smaller than 1.5 m.

Spatial Variability.

Of five variables examined only catch can depths and profile water content showed consistent spatial structure over time. The variogram for catch can depths was fit well by a spherical model and that for profile water contents with a linear model. The relative variograms for both these variables were stable over time and allowed the fitting of a single relative variogram model to each data set with the result that the relative variogram model could be scaled to provide a model for any particular day's data by simply multiplying the nugget and sill by the variable's mean squared. The usefulness of this was enhanced by the fact that the mean value could be reliably estimated by using a location identified as representative of the mean. These locations were identified by the time invariance analysis of Chapter 8. Thus a strong link was demonstrated between the existence of time invariance for a variable and the usefulness of kriging on that variable.

There was little discernible spatial structure for evaporation nor for the change in storage due to irrigation. The structure apparent for evaporation data from days 332 and 333, Experiment 3, is associated with an influx of warm air causing mean daily air temperature to rise 3 °C.

Data from some days seemed to show spatial structure for the midday temperature difference between dry and drying soil.

However, data from many other days showed no spatial structure. There appeared to be some structure on the warm day 333 during Experiment 3. There was more structure apparent for the first 2 days after Irrigations 1 and 2 of Experiment 2. It was much warmer during the late March - early April time period of Experiment 2 than during the November - early December period of Experiment 3. Thus it appears that the appearence of spatial structure associated with soil surface temperature may be linked to high ambient temperature or high potential evapotranspiration.

The 'here today - gone tomorrow' nature of spatial structure associated with evaporation and surface temperature data makes questionable the utility of spatial variability analysis of these variables. In particular the idea, that cokriging using evaporation and temperature data could be used to reduce the number of ML samples needed to estimate evaporation, is shown to be questionable due to the lack of time invariant spatial structure.

Soil surface temperature is a rapidly changing environmental variable. In Chapter 3 it was shown that the surface temperature at midday could vary by up to 10 °C over the 30 to 40 minutes necessary to measure all 57 locations in the field. Changes in cloud cover and wind speed were associated with these temperature changes. Such rapid temperature variations render problematic the task of measuring the spatial structure of soil surface temperature. The geostatistical approach was initially developed to study the spatial structure of ore grades, a variable that changes with the millenia. It is perhaps asking too much to apply these same techniques to labile environmental variables.

Recommendations.

The combination of time invariance and spatial variability analysis is useful for the prediction of slowly changing variables such as the profile water content for bare soil. Other studies have indicated that the spatial variability of profile water content under plant cover in not constant so care must be used in extending the results reported here to other conditions. Evaporation and midday surface temperature data were not clearly time invariant and had inconsistent spatial structure. Thus no recommendation for the use of these techniques can be made for those variables.

Irrigation Uniformity

Irrigation uniformity under the low pressure lateral move sprinkler used for this study was reasonable for such a systme. Christiansen's uniformity coefficient values were close to 0.83 for uniformity of both catch can data and of the profile water content after each of three irrigations. However, data on change in storage due to irrigation showed that the uniformity of profile water contents was not a direct result of the uniformity of application as measured by catch cans. Under different conditions of field topography the results could have been much different using the same sprinkler system. Future studies of irrigation uniformity under low pressure sprinkler, or other overhead systems that cause ponding, should include measurement of the profile water content as an indicator of uniformity rather than relying strictly on catch can data or data from other types of surface collectors.